

Search for anomalous $WW\gamma$ and WWZ couplings with polarized e -beam at the LHeC

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Abstract

We examine the potential of the $ep \rightarrow \nu_e q \gamma X$ and $ep \rightarrow \nu_e q Z X$ processes to search for the anomalous couplings of $WW\gamma$ and WWZ vertices at the LHeC with the electron beam energy of $E_e = 60$ GeV and $E_e = 140$ GeV. The difference of maximum and minimum bounds on the anomalous couplings, $(\delta\Delta\kappa_\gamma, \delta\lambda_\gamma)$ and $(\delta\Delta\kappa_Z, \delta\lambda_Z)$ are obtained as $(0.990, 0.122)$ and $(0.362, 0.012)$ without electron beam polarization at the beam energy of $E_e = 140$ GeV for an integrated luminosity of $L_{int} = 100 \text{ fb}^{-1}$, respectively. With the possibility of e -beam polarization, we obtain more improved results as $(0.975, 0.118)$ and $(0.285, 0.009)$ for $(\delta\Delta\kappa_\gamma, \delta\lambda_\gamma)$ and $(\delta\Delta\kappa_Z, \delta\lambda_Z)$, respectively. The results are found to be comparable with the current experimental limits obtained from two-parameter analysis at the lepton and hadron colliders. It is found that the limits on the anomalous couplings $(\Delta\kappa_Z, \lambda_Z)$ through the process $ep \rightarrow \nu_e q Z X$ at the LHeC can further improve the current experimental limits.

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I. INTRODUCTION

Triple gauge boson interactions are the consequence of the $SU(2) \times U(1)$ gauge symmetry of the standard model (SM). A precise determination of the trilinear gauge boson couplings are necessary to test the validity of the SM and the presence of new physics up to a high energy scale. Since the tree-level couplings of the $WW\gamma$ and WWZ vertices are fixed by the SM, any deviations from their SM values would indicate the new physics beyond the SM. Possible types of the collisions of the accelerated particles will extend the level of precision to triple couplings of the gauge bosons. The photoproduction of W and Z bosons have been studied in the baseline of lepton-hadron coliders HERA+LC [1] and the Large Hadron electron Collider (LHeC) [2]. An investigation of the potential of the LHeC to probe anomalous $WW\gamma$ coupling has also been presented in Ref. [3].

The present bounds on the anomalous $WW\gamma$ and WWZ couplings are provided by the LEP [4], Tevatron [5, 6] and LHC [7, 8] experiments. Recently, the ATLAS [7] and CMS [8] Collaborations have established updated constraints on the anomalous $WW\gamma$ and WWZ couplings from the $\gamma W(Z)$ and W^+W^- production processes. The best available constraints on $\Delta\kappa_\gamma$, λ_γ , $\Delta\kappa_Z$ and λ_Z obtained from one parameter analysis at different experiments are summarized in Table I.

The limits based on one-parameter analysis at 95% C.L. on the $\Delta\kappa_\gamma$ and λ_γ from ATLAS Collaboration with $W\gamma$ production process data at $\sqrt{s} = 7$ TeV and $L_{int} = 4.6 \text{ fb}^{-1}$ are $(-0.135, 0.190)$ and $(-0.065, 0.061)$ [7]. Same limits from the 95% C.L. two-parameter analysis are $(-0.420, 0.480)$ for $\Delta\kappa_\gamma$ and $(-0.068, 0.062)$ for λ_γ . Two-parameter 95% C.L. limits on anomalous couplings $\Delta\kappa_Z$ and λ_Z are given as $(-0.045, 0.045)$ and $(-0.063, 0.063)$, respectively.

According to CMS Collaboration, one-parameter 95% C.L. limits are $(-0.210, 0.220)$ and $(-0.048, 0.048)$ for $\Delta\kappa_\gamma$ and λ_γ from $W\gamma$ production process at $\sqrt{s} = 7$ TeV and $L_{int} = 5 \text{ fb}^{-1}$ [8]. From two-parameter contours, the upper limits for $\Delta\kappa_\gamma$ and λ_γ are obtained as $(-0.250, 0.250)$ and $(-0.050, 0.042)$ at the 95% C.L. while one-parameter 95% C.L. limits on $\Delta\kappa_Z$ and λ_Z are $(-0.160, 0.157)$ and $(-0.048, 0.048)$ from W^+W^- production process at $\sqrt{s} = 7$ TeV. Here, the relation $\Delta\kappa_Z = \Delta g_1^Z - \Delta\kappa_\gamma \cdot \tan^2 \theta_W$ is used to extract some of the limits in the LEP scenario. The results from ATLAS and CMS experiments based on two parameter analysis of the anomalous couplings are given in Table II.

Table I: The available 95% C.L. bounds on anomalous couplings $(\Delta\kappa_\gamma, \lambda_\gamma)$ and $(\Delta\kappa_Z, \lambda_Z)$ from the data at LEP, Tevatron, and LHC experiments. In each case the parameter listed is varied while the others are fixed to their SM values.

	LEP[4]	CDF[5]	D0[6]	ATLAS[7]	CMS[8]
$\Delta\kappa_\gamma$	[-0.099, 0.066]	[-0.460, 0.390]	[-0.158, 0.255]	[-0.135, 0.190]	[-0.210, 0.220]
λ_γ	[-0.059, 0.017]	[-0.180, 0.170]	[-0.036, 0.044]	[-0.065, 0.061]	[-0.048, 0.048]
$\Delta\kappa_Z$	[-0.073, 0.050]	[-0.414, 0.470]	[-0.110, 0.131]	[-0.061, 0.093]	[-0.160, 0.157]
λ_Z	[-0.059, 0.017]	[-0.140, 0.150]	[-0.036, 0.044]	[-0.062, 0.065]	[-0.048, 0.048]

Table II: The available 95% C.L. two-parameter bounds on anomalous couplings $(\Delta\kappa_\gamma, \lambda_\gamma)$ and $(\Delta\kappa_Z, \lambda_Z)$ from the ATLAS and CMS experiments. The difference of maximum and minimum bounds are show in last two column.

	ATLAS[7]	CMS[8]	ATLAS (max-min)	CMS (max-min)
$\Delta\kappa_\gamma$	[-0.420, 0.480]	[-0.250, 0.250]	0.900	0.500
λ_γ	[-0.068, 0.062]	[-0.050, 0.042]	0.130	0.092
$\Delta\kappa_Z$	[-0.045, 0.045]	[-0.160, 0.180]	0.090	0.340
λ_Z	[-0.063, 0.063]	[-0.055, 0.055]	0.126	0.110

In this study, we examined the $ep \rightarrow \nu_e q \gamma X$ and $ep \rightarrow \nu_e q Z X$ processes with anomalous $WW\gamma$ and WWZ couplings at the high energy electron-proton collider namely, the Large Hadron electron Collider (LHeC). This collider is considered to be realised by accelerating electrons in a linear accelerator (linac) to 60 – 140 GeV and colliding them with the 7 TeV protons incoming from the LHC. We take into account the possibility of the electron beam polarization at LHeC which extends the sensitivity to anomalous triple gauge boson couplings. The anticipated integrated luminosity is about at the order of 10 and 100 fb⁻¹ [9].

II. ANOMALOUS COUPLINGS

The $WW\gamma$ and WWZ interaction vertices are described by an effective Lagrangian with the coupling constants $g_{WW\gamma}$ and g_{WWZ} and dimensionless parameter pairs $(\kappa_\gamma, \lambda_\gamma)$ and

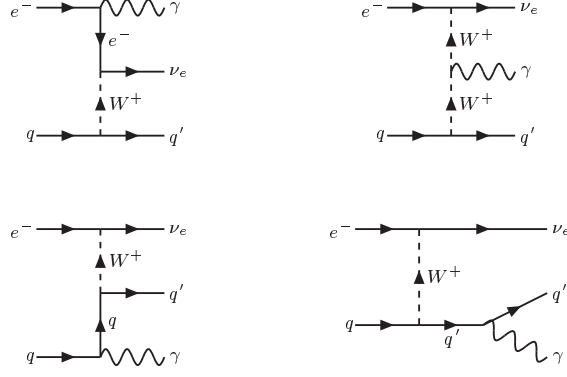


Figure 1: Representative Feynman diagrams for subprocesses $eq \rightarrow \nu\gamma q$.

(κ_Z, λ_Z) ,

$$\begin{aligned} \mathcal{L} = & ig_{WW\gamma}[g_1^\gamma(W_{\mu\nu}^\dagger W^\mu A^\nu - W^{\mu\nu}W_\mu^\dagger A_\nu) + \kappa_\gamma W_\mu^\dagger W_\nu A^{\mu\nu} + \frac{\lambda_\gamma}{m_W^2}W_{\rho\mu}^\dagger W_\nu^\mu A^{\nu\rho}] \\ & + ig_{WWZ}[g_1^Z(W_{\mu\nu}^\dagger W^\mu Z^\nu - W^{\mu\nu}W_\mu^\dagger Z_\nu) + \kappa_Z W_\mu^\dagger W_\nu Z^{\mu\nu} + \frac{\lambda_Z}{m_W^2}W_{\rho\mu}^\dagger W_\nu^\mu Z^{\nu\rho}] \end{aligned} \quad (1)$$

where $g_{WW\gamma} = g_e = g\sin\theta_W$ and $g_{WWZ} = g\cos\theta_W$. In general these vertices involve six C and P conserving couplings [10]. However, the electromagnetic gauge invariance requires that $g_1^\gamma = 1$. The anomalous couplings are defined as $\kappa_V = 1 + \Delta\kappa_V$ where $V = \gamma, Z$ and $g_1^Z = 1 + \Delta g_1^Z$. The $W_{\mu\nu}$, $Z_{\mu\nu}$ and $A_{\mu\nu}$ are the field strength tensors for the W - boson, Z -boson and photon, respectively.

The values of the couplings $\kappa_\gamma = \kappa_Z = 1$ and $\lambda_\gamma = \lambda_Z = 0$ correspond to the case of the SM. Since unitarity restricts the $WW\gamma$ and WWZ couplings to their SM values at very high energies, the triple gauge couplings are modified as $\Delta\kappa_V(q^2) = \Delta\kappa_V(0)/(1 + q^2/\Lambda^2)^2$ and $\lambda_V(q^2) = \lambda_V(0)/(1 + q^2/\Lambda^2)^2$ where $V = \gamma, Z$. The q^2 is the square of momentum transfer into the process and Λ is the new physics energy scale. The $\Delta\kappa_V(0)$ and $\lambda_V(0)$ are the values of the anomalous couplings at $q^2 = 0$. We assume the values of the anomalous couplings remain approximate constant in the interested energy scale. We have implemented interactions terms in the CalcHEP [11].

III. PRODUCTION CROSS SECTIONS

According to the effective Lagrangian the anomalous vertices for triple gauge interactions $WW\gamma$ and WWZ are presented in the Feynman graphs as shown in Fig. 1 and Fig. 2. In

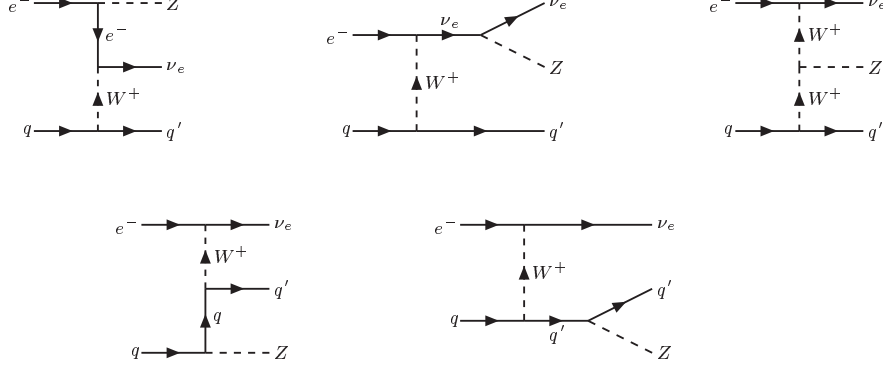


Figure 2: Representative Feynman diagrams for subprocesses $eq \rightarrow \nu Z q$.

order to calculate the cross sections for the process $ep \rightarrow \nu_e q \gamma X$ and $ep \rightarrow \nu_e q Z X$, we apply the transverse momentum cut on photon and jet as $p_T^\gamma > 50$ GeV, $p_T^j > 20$ GeV; missing transverse momentum cut $p_T^\nu > 20$ GeV, pseudorapidity cuts $|\eta_{\gamma,j}| < 3.5$; a cone radius cut between photons and jets $\Delta R_{\gamma,j} > 1.5$. Using these cuts and CTEQ6L [12] for parton distribution functions, the total cross sections of the process $ep \rightarrow \nu \gamma q X$ as a function of anomalous couplings $\Delta\kappa_\gamma$ and λ_γ for $E_e = 60$ GeV (140 GeV) with ($P_e = \pm 0.8$) and without ($P_e = 0$) electron beam polarization are presented in Figs. 3 and 4 (Figs. 5 and 6), respectively. It is clear from these figures that the polarization ($P_e = -0.8$) enhances the cross sections according to the unpolarized case.

The cross sections depending on anomalous couplings $\Delta\kappa_Z$ and λ_Z of the process $ep \rightarrow \nu Z q X$ for $E_e = 60$ GeV (140 GeV) with ($P_e = \pm 0.8$) and without ($P_e = 0$) electron beam polarization are presented in Figs. 7 and 8 (Figs. 9 and 10), respectively.

IV. ANALYSIS

In order to estimate the sensitivity to the anomalous $WW\gamma$ and WWZ couplings, we use two-parameter χ^2 function:

$$\chi^2(\Delta\kappa_V, \lambda_V) = \left(\frac{\sigma_{SM} - \sigma(\Delta\kappa_V, \lambda_V)}{\Delta\sigma_{SM}} \right)^2 \quad (2)$$

where $\Delta\sigma_{SM} = \sigma_{SM} \sqrt{\delta_{stat.}^2}$ with $\delta_{stat.} = 1/\sqrt{N_{SM}}$ and $N_{SM} = \sigma_{SM} \cdot \epsilon \cdot L_{int}$. In our calculations, we consider that two of the couplings $(\Delta\kappa, \lambda)$ are assumed to deviate from their SM value. We estimate the sensitivity to the anomalous couplings at LHeC for the integrated

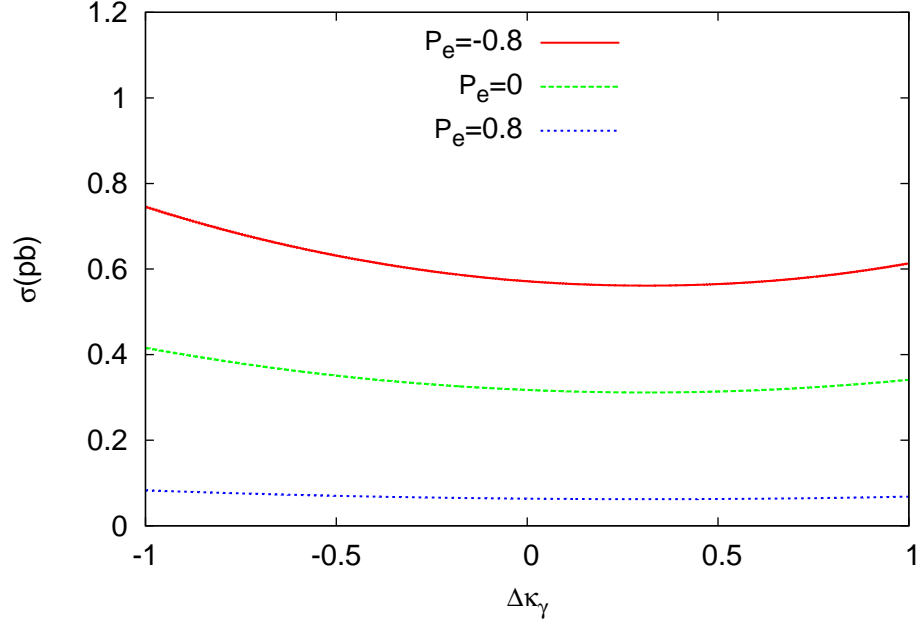


Figure 3: The cross section depending on anomalous coupling $\Delta\kappa_\gamma$ of the process $ep \rightarrow \nu\gamma qX$ for $E_e = 60$ GeV.

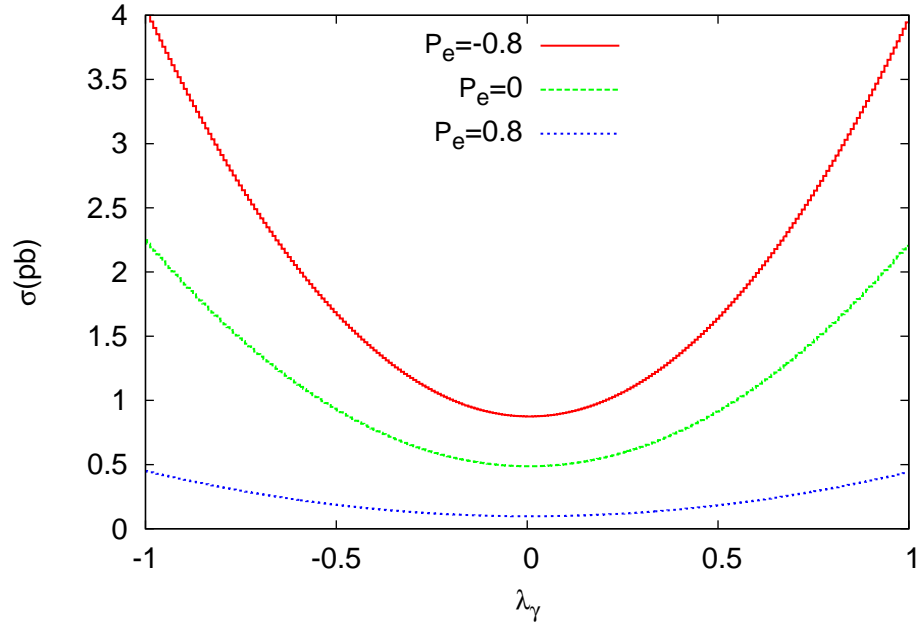


Figure 4: The cross section depending on anomalous coupling λ_γ of the process $ep \rightarrow \nu\gamma qX$ for $E_e = 60$ GeV.

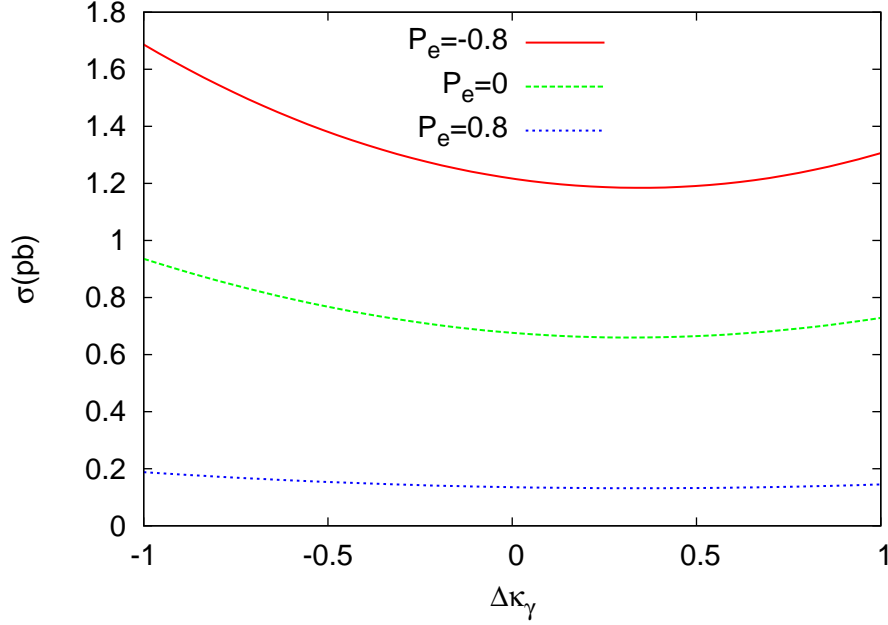


Figure 5: The same as Fig 3 but for $E_e = 140$ GeV.

luminosities of 10 and 100 fb^{-1} . The contour plots in $\Delta\kappa_\gamma - \lambda_\gamma$ plane for the integrated luminosities of 10 fb^{-1} and 100 fb^{-1} at electron beam energies $E_e = 60$ (140) GeV with different polarizations are given in Figs. 11-16. For the process $ep \rightarrow \nu_e q Z X$, we make analysis of the signal and backgrounds when Z decays into leptonically, $Z \rightarrow l^+ l^-$ where $l = e, \mu$. The contour plots in $\Delta\kappa_Z - \lambda_Z$ plane for the integrated luminosities of 10 fb^{-1} and 100 fb^{-1} at electron beam energies $E=60$ (140) GeV with different polarizatons are presented in Figs. 17-22.

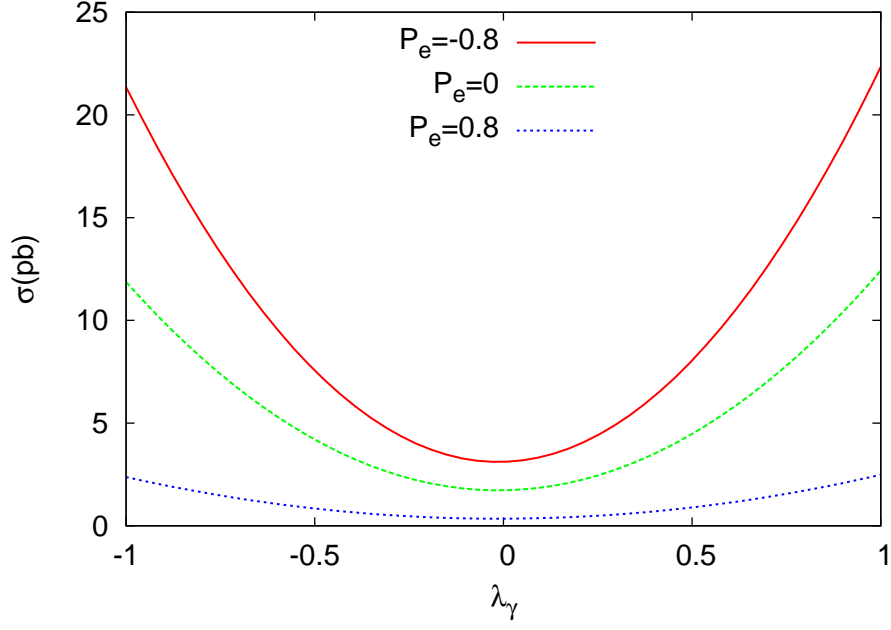


Figure 6: The same as Fig 4 but for $E_e = 140$ GeV.

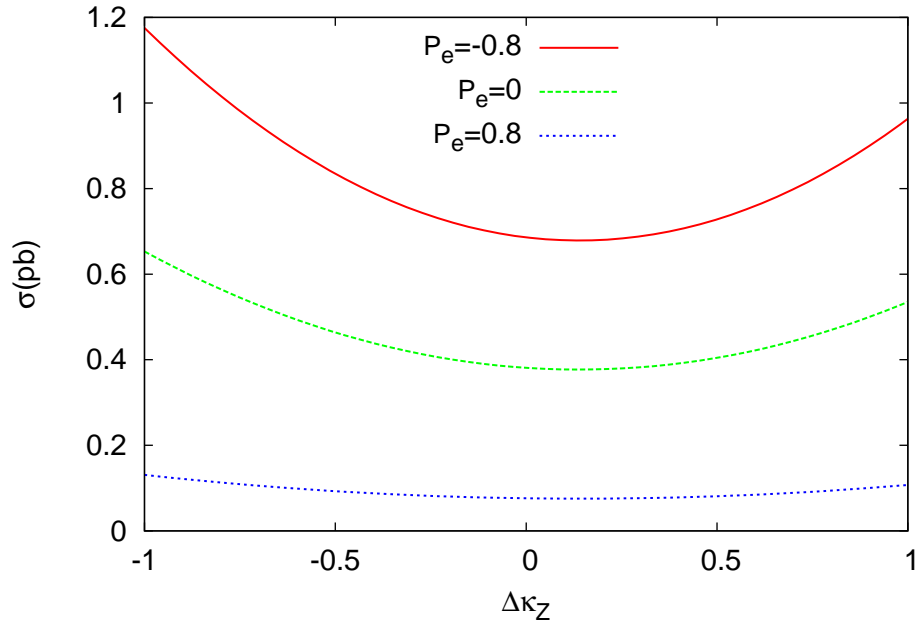


Figure 7: The cross section depending on anomalous $\Delta\kappa_z$ coupling of the process $ep \rightarrow \nu Z q X$ for $E_e = 60$ GeV.

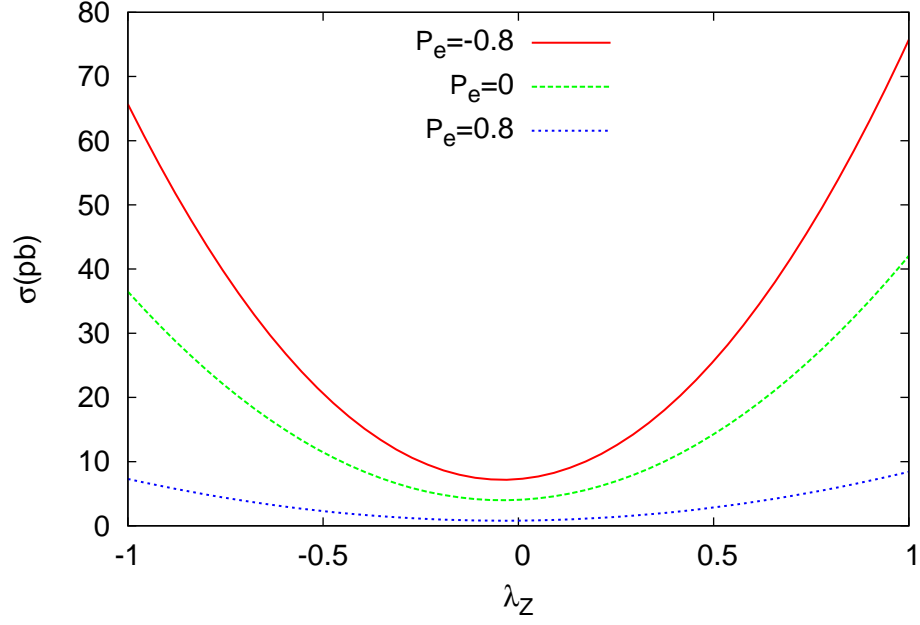


Figure 8: The cross section depending on anomalous λ_z coupling of the process $ep \rightarrow \nu Z q X$ for $E_e = 60$ GeV. .

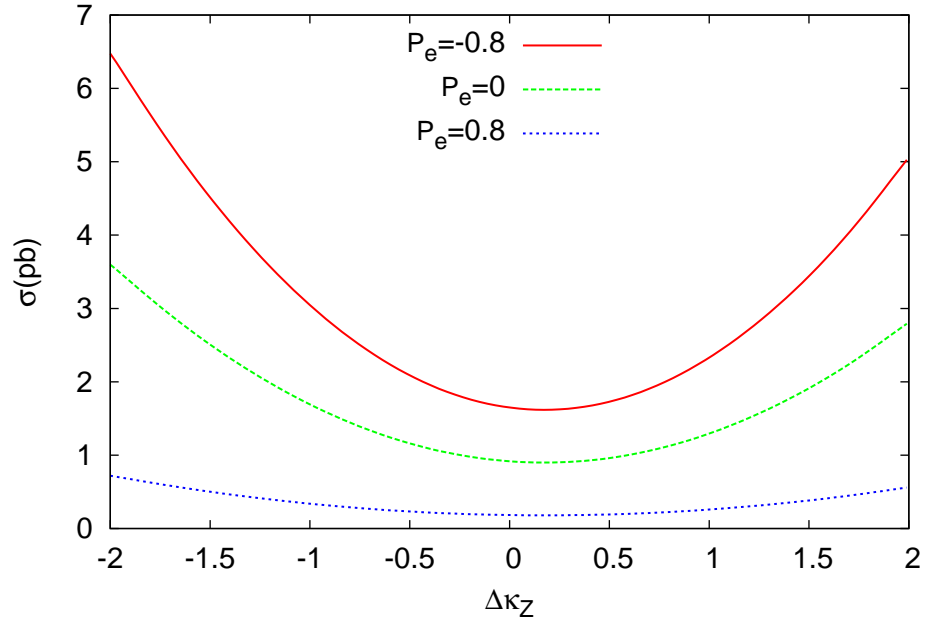


Figure 9: The same as Fig 7 but for $E_e = 140$ GeV.

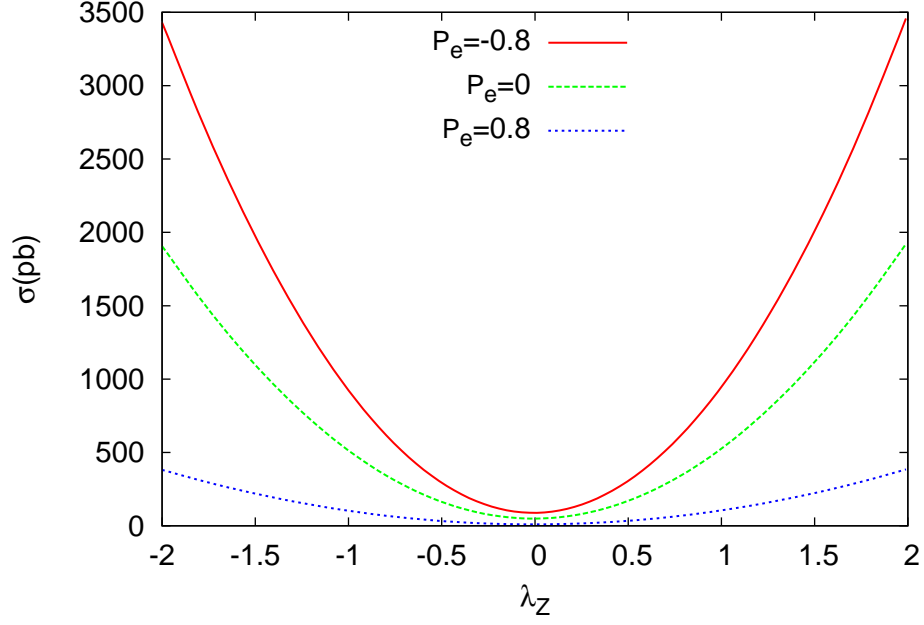


Figure 10: The same as Fig 8 but for $E_e = 140$ GeV. .

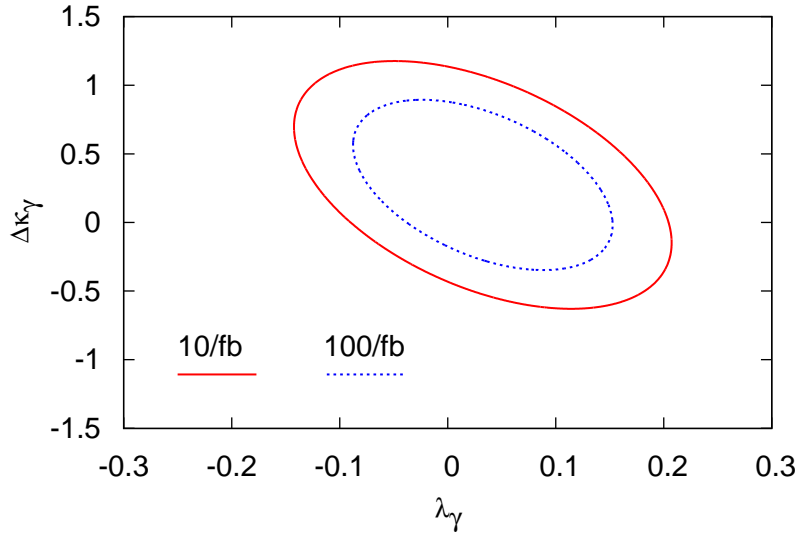


Figure 11: Contour plots in the $\lambda_\gamma - \Delta\kappa_\gamma$ plane for the integrated luminosity of 10 fb^{-1} and 100 fb^{-1} at electron beam energy $E_e = 60$ GeV with the beam polarization $P_e = 0.8$.

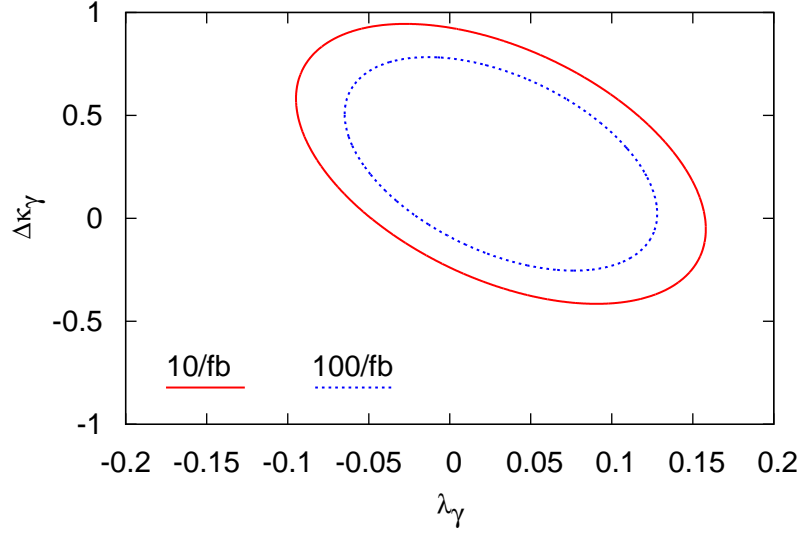


Figure 12: The same as Fig. 11, but for $P_e = 0$.

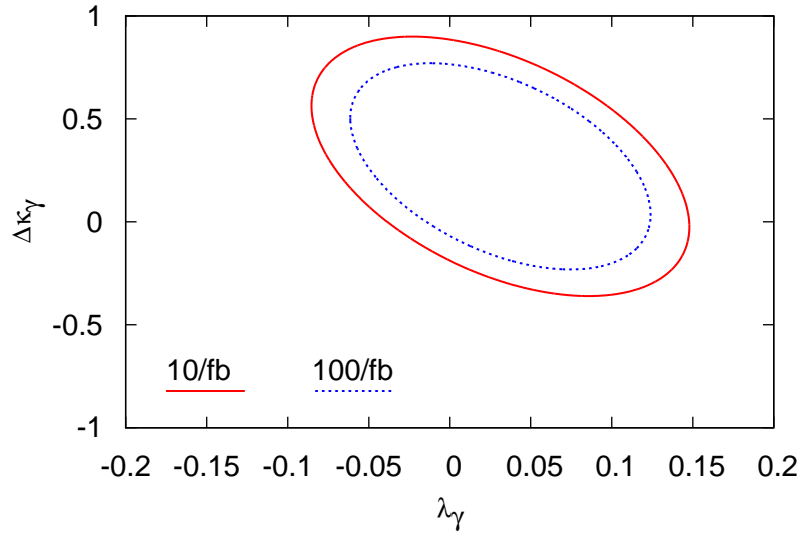


Figure 13: The same as Fig. 11, but for $P_e = -0.8$.

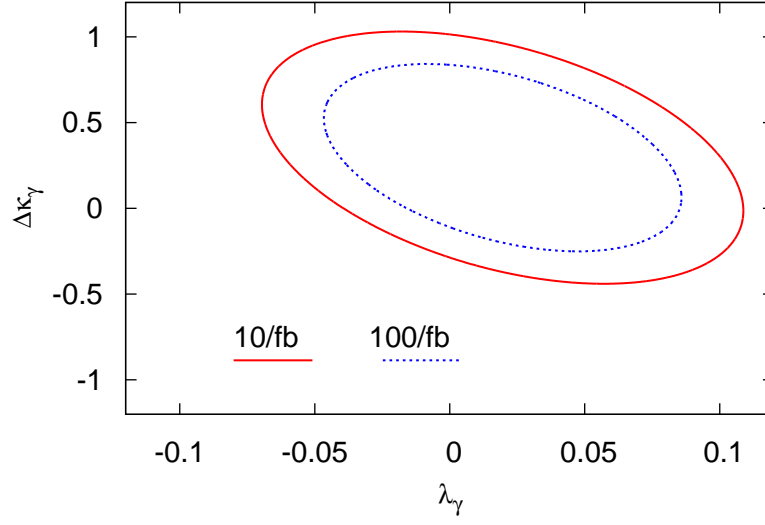


Figure 14: Contour plots in the $\lambda_\gamma - \Delta\kappa_\gamma$ plane for the integrated luminosity of 10 fb⁻¹ and 100 fb⁻¹ at electron beam energy $E_e = 140$ GeV with polarization $P_e = 0.8$.

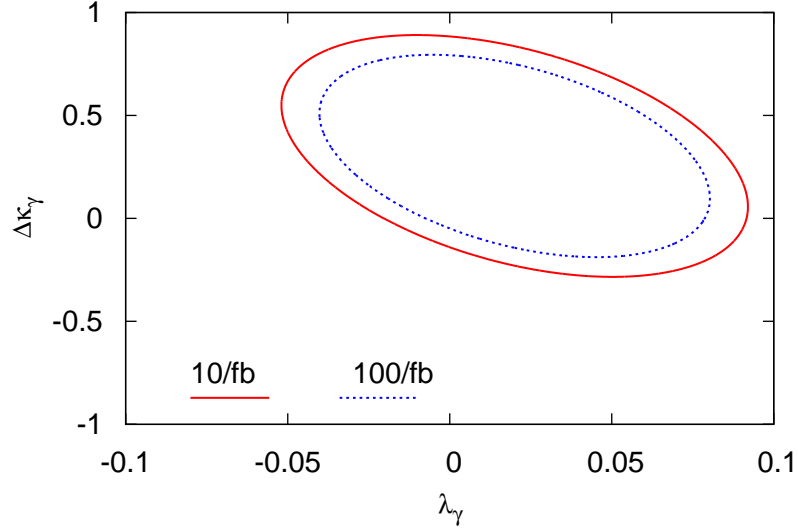


Figure 15: The same as Fig. 14, but for $P_e = 0$.

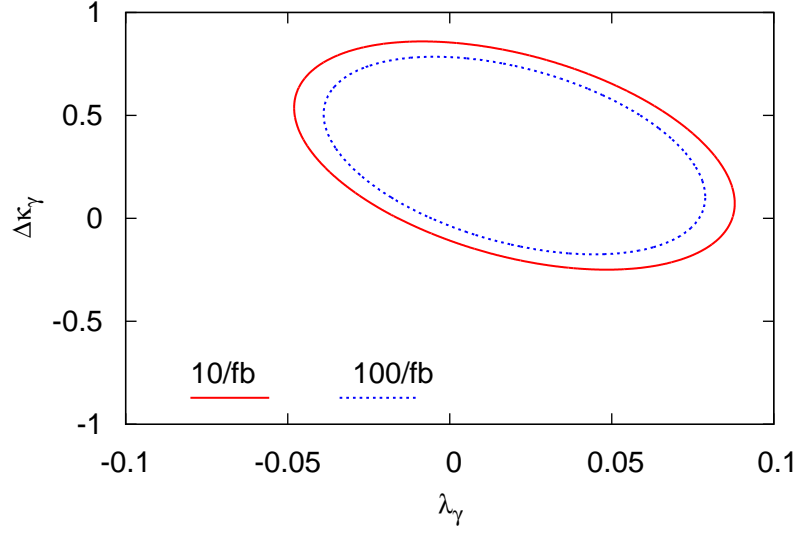


Figure 16: The same as Fig. 14, but for $P_e = -0.8$ GeV.

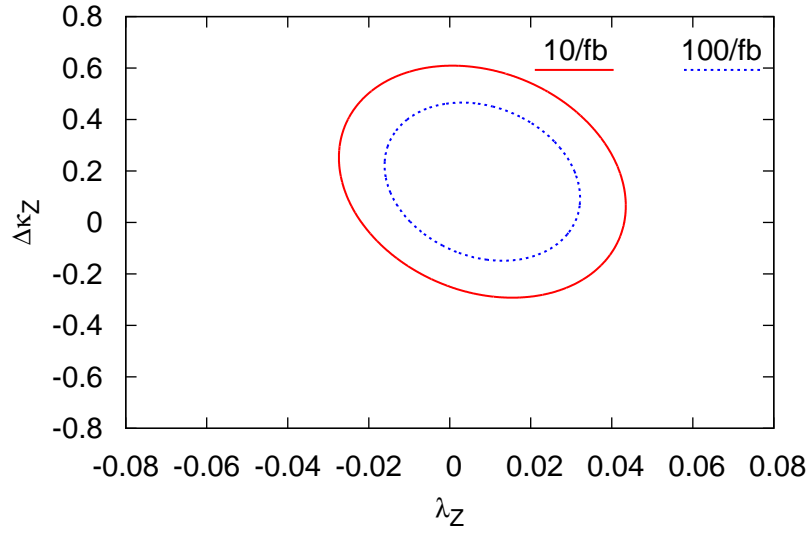


Figure 17: Contour plots in the $\lambda_z - \Delta\kappa_z$ plane for the integrated luminosity of 10 fb^{-1} and 100 fb^{-1} at electron beam energy $E_e = 60$ GeV with polarization $P_e = 0.8$.

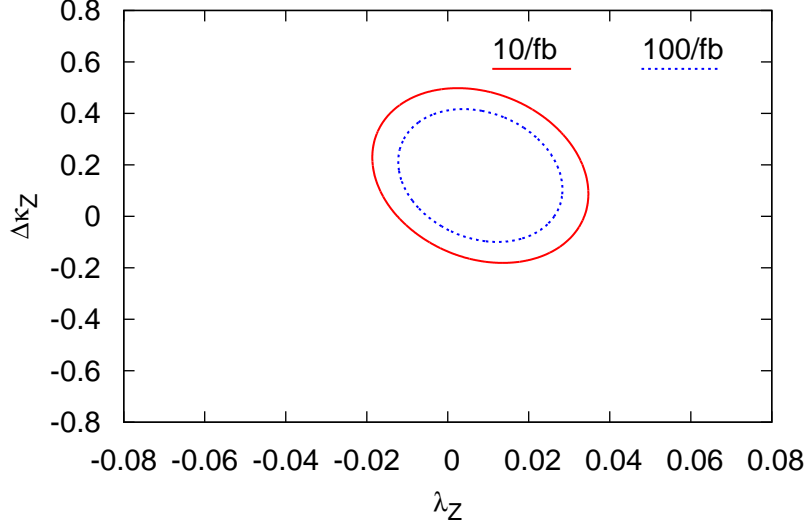


Figure 18: The same as Fig. 17, but for $P_e = 0$.

The difference of maximum and minimum bounds on the anomalous couplings $\Delta\kappa_V$ and λ_V (where $V = \gamma, Z$) can be written as

$$\delta\Delta\kappa_V = \Delta\kappa_V^{\max} - \Delta\kappa_V^{\min}, \quad \delta\lambda_V = \lambda_V^{\max} - \lambda_V^{\min} \quad (3)$$

The limits on anomalous couplings and the difference of maximum and minimum bounds for electron beam energies $E_e = 60$ and 140 GeV with integrated luminosities $L_{int} = 10$ and 100 fb^{-1} at LHeC with the unpolarized (polarized) electron beam are given in Tables III-VI.

Table III: The limits on the anomalous couplings and the difference of maximum and minimum bounds for electron beam energy of $E_e=60$ GeV with $L_{int}=10 \text{ fb}^{-1}$ for polarized and unpolarized electron beam.

P_e	$\Delta\kappa_\gamma$	$\delta\Delta\kappa_\gamma$	λ_γ	$\delta\lambda_\gamma$	$\Delta\kappa_Z$	$\delta\Delta\kappa_Z$	λ_Z	$\delta\lambda_Z$
-0.8	[-0.366, 0.899]	1.265	[-0.085, 0.148]	0.233	[-0.152, 0.471]	0.623	[-0.016, 0.033]	0.049
0	[-0.421, 0.940]	1.361	[-0.094, 0.159]	0.253	[-0.180, 0.498]	0.677	[-0.018, 0.035]	0.053
0.8	[-0.641, 1.177]	1.818	[-0.141, 0.208]	0.349	[-0.293, 0.611]	0.904	[-0.027, 0.044]	0.071

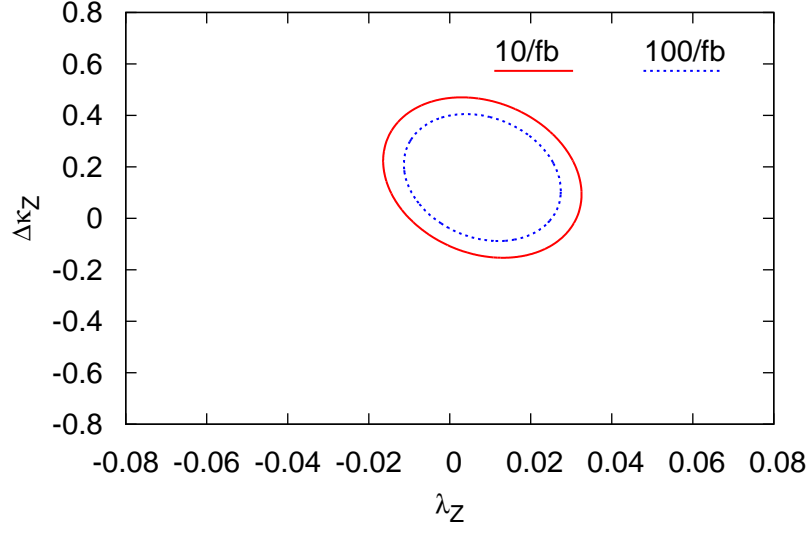


Figure 19: The same as Fig. 17, but for $P_e = -0.8$.

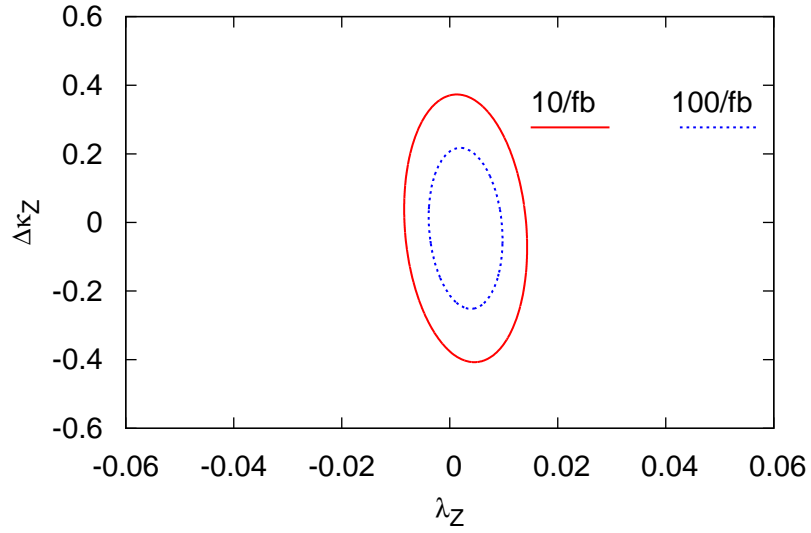


Figure 20: Contour plots in the $\lambda_z - \Delta\kappa_z$ plane for the integrated luminosity of 10 fb^{-1} and 100 fb^{-1} at electron beam energy $E_e = 140 \text{ GeV}$ with polarization $P_e = 0.8$.

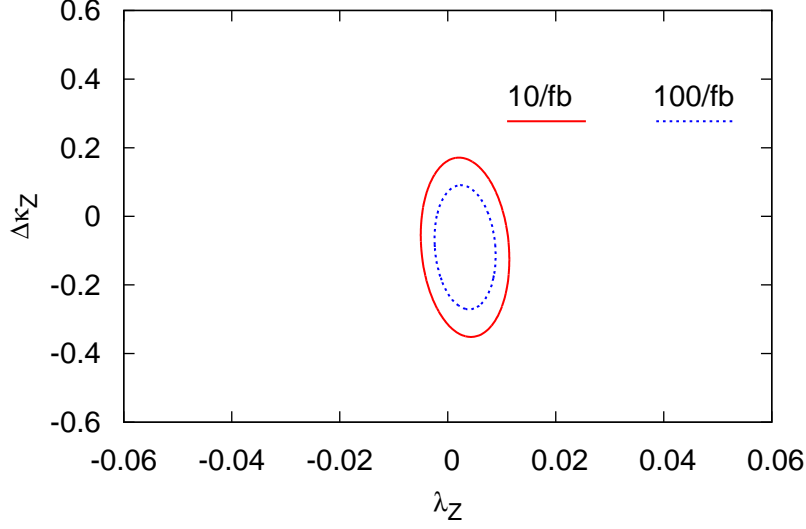


Figure 21: The same as Fig. 20, but for $P_e = 0$.

Table IV: Same as Table II but for $L_{int}=100 \text{ fb}^{-1}$.

P_e	$\Delta\kappa_\gamma$	$\delta\Delta\kappa_\gamma$	λ_γ	$\delta\lambda_\gamma$	$\Delta\kappa_Z$	$\delta\Delta\kappa_Z$	λ_Z	$\delta\lambda_Z$
-0.8	[-0.237, 0.771]	1.008	[-0.061, 0.124]	0.185	[-0.088, 0.405]	0.493	[-0.011, 0.027]	0.038
0	[-0.257, 0.777]	1.034	[-0.064, 0.128]	0.192	[-0.104, 0.412]	0.516	[-0.012, 0.028]	0.040
0.8	[-0.356, 0.893]	1.249	[-0.087, 0.153]	0.240	[-0.147, 0.465]	0.612	[-0.016, 0.032]	0.048

V. CONCLUSIONS

The $WW\gamma$ and WWZ anomalous interactions through the process $ep \rightarrow \nu_e q \gamma X$ and $ep \rightarrow \nu_e q Z X$ can be studied independently at the LHeC. We obtain two-parameter accessible ranges of triple gauge boson anomalous couplings at LHeC with the polarized and unpolarized beam at the energy of $E_e = 60 \text{ GeV}$ and $E_e = 140 \text{ GeV}$. Our limits compare with the results from two-parameter analysis given by ATLAS and CMS Collaborations [7, 8]. We find that the LHeC with polarized electron beam improves the bounds on anomalous couplings. The LHeC will give complementary information about anomalous couplings compared to Tevatron and LHC.

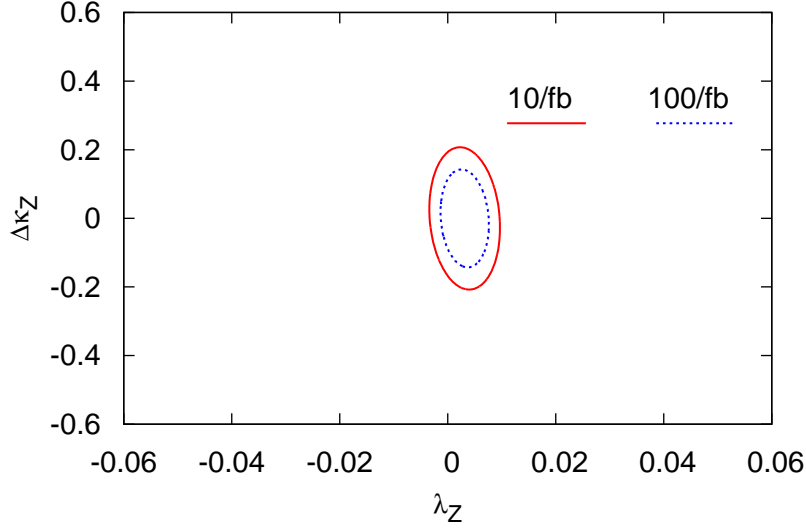


Figure 22: The same as Fig. 20, but for $P_e = -0.8$.

Table V: The limits on the anomalous couplings and the difference of maximum and minimum bounds for electron beam energy of $E_e=140$ GeV with $L_{int}=10 \text{ fb}^{-1}$ for polarized and unpolarized electron beam.

P_e	$\Delta\kappa_\gamma$	$\delta\Delta\kappa_\gamma$	λ_γ	$\delta\lambda_\gamma$	$\Delta\kappa_Z$	$\delta\Delta\kappa_Z$	λ_Z	$\delta\lambda_Z$
-0.8	[-0.255, 0.865]	1.120	[-0.049, 0.088]	0.137	[-0.208, 0.207]	0.415	[-0.003, 0.010]	0.013
0	[-0.288, 0.895]	1.183	[-0.052, 0.092]	0.144	[-0.350, 0.170]	0.520	[-0.005, 0.012]	0.017
0.8	[-0.255, 1.035]	1.120	[-0.070, 0.109]	0.179	[-0.407, 0.373]	0.780	[-0.008, 0.014]	0.022

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Table VI: Same as Table III but for $L_{int}=100 \text{ fb}^{-1}$.

P_e	$\Delta\kappa_\gamma$	$\delta\Delta\kappa_\gamma$	λ_γ	$\delta\lambda_\gamma$	$\Delta\kappa_Z$	$\delta\Delta\kappa_Z$	λ_Z	$\delta\lambda_Z$
-0.8	[-0.182, 0.793]	0.975	[-0.039, 0.079]	0.118	[-0.143, 0.142]	0.285	[-0.001, 0.008]	0.009
0	[-0.192, 0.798]	0.990	[-0.041, 0.081]	0.122	[-0.273, 0.089]	0.362	[-0.003, 0.009]	0.012
0.8	[-0.251, 0.844]	1.095	[-0.047, 0.086]	0.133	[-0.253, 0.215]	0.468	[-0.004, 0.010]	0.014

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